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Lightning-Induced Voltages on Overhead Distribution Lines: Theoretical and Experimental Investigation of related Problems and their Impact on Power Quality

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Recent power quality studies have been focused on the source-identification of voltage disturbances at distribution network busses. This paper describes a method aimed at correlating indirect-lightning events with power systems relay operations, associated with voltage dips. The proposed method, based on the coordinated use of the Italian lightning location system CESI-SIRF, the Italian monitoring system of protection manoeuvres CESI-SAM, and the availability of an advanced simulation tool for the accurate simulation of lightning-induced voltages on complex power networks, namely the LIOV-EMTP code, is applied to the real case of an Italian distribution system.
The LIOV-EMTP code is also employed along with a statistical procedure based on the Monte Carlo method to carry out a statistical analysis aimed at assessing the lightning performance of a typical Italian distribution line.

Keywords: lightning-induced overvoltages – lightning location systems – power quality – voltage dip/sag.

1. INTRODUCTION

Transient disturbances on distribution networks, which seriously affect the power quality, are certainly more frequent during thunderstorms [1,2]. Lightning activity, and in particular the so-called lightning ‘indirect’ effects [3] are therefore considered as one of the main causes for power quality problem. Due to the limited height of medium and low voltage distribution networks compared to that of the structures in their vicinity, indirect lightning return strokes are indeed more frequent events than direct strokes [4]. Overvoltages induced by nearby lightning on distribution networks may cause phase-to-ground and phase-to-phase flashovers which need, for their removal, the use of recloser breakers which are controlled by relevant relays. The operation of these breakers is associated with a temporal decrease of the voltage supplied to customers, also known as voltage dip or sag; a phenomenon which

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eventually disappears after the successful reclosure (if any) of the breaker. Voltage dips cause serious malfunction of a large number of apparatus [5] and represent a severe limitation of the electrical energy power quality. In electrical systems located in regions with high isokeraunic levels, it is reported that over 80% of the voltage dips that cause apparatus malfunction are originated by lightning [1,2]. Nevertheless, lightning activity is not the only responsible for the occurrence of voltage dips related to the thunderstorms. In fact, other natural causes associated with thunderstorms such as the wind effect may cause short circuits (branch of trees-ground; conductor-conductor). Consequently, the correlation between relay operation and lightning events becomes of crucial interest for the identification of the source of voltage dips [3,6,7]. Indeed, appropriate insulation coordination of distribution lines can be accomplished only after having assessed how far lightning is the real responsible of fault events.

Data from Lightning Location Systems (LLS), which provide an estimation of both lightning flash location and return-stroke current amplitude, can certainly be used to understand whether lightning is indeed the real cause of relay (and breaker) operation, and consequently of voltage dips, during thunderstorms. Due to the complexity of the problem, however, the data coming from LLS, namely the lightning stroke location and the estimation of the lightning current amplitude, are in general not sufficient to infer the origin of voltage dips. It is necessary, also, to suitably integrate these data with those provided by power system monitoring (relevant to the relay operation) or – more generally – by distributed power quality monitoring systems [8], and with simulation results obtained by using advanced simulation tools, able to evaluate lightning-induced voltages on complex power networks.

The present paper reports some results of a research activity aimed at the appraisal of the correlation between faults experienced by a large distribution system located in the northern part of Italy and lightning events. The work is based on the coordinated use of a) the Italian Lightning Location System CESI-SIRF [9,10], b) the Italian monitoring system of relay operations CESI-SAM [7] and c) an advanced modelling/computing tool, known as LIOV-EMTP [11-14]. LIOV-EMTP is a computer tool developed in the framework of an international research cooperation (involving the University of Bologna, the Swiss Federal Institute of Technology (Lausanne), the University of Rome 'La Sapienza' and CESI, for the estimation of the response of distribution networks located above a lossy ground illuminated by an external Lightning Electromagnetic Pulse (LEMP).

The lightning performance of a typical Italian distribution line will also be evaluated and discussed using an advanced statistical procedure based on the Monte Carlo method and on the capabilities of the LIOV-EMTP code [15,16].

2. CORRELATING INDIRECT LIGHTNING WITH POWER DISTRIBUTION SYSTEM FAULTS: COORDINATED USE OF FIELD DATA AND COMPUTER TOOLS

As mentioned in the Introduction, the procedure we developed for the appraisal of the correlation between distribution system faults and lightning events is based on the availability and the use of:

- the Italian lightning location system (CESI-SIRF);
- the Italian monitoring systems for relay operation (CESI-SAM);
- the LIOV-EMTP code.

2.1 Italian lightning location system (CESI-SIRF)

The Italian lightning location system CESI-SIRF ('Sistema Italiano Rilevamento Fulmini'), consists of 16 sensors located throughout Italian territory. In addition to that, data from Austrian, French and Swiss sensors located in the northern part of the network are made available to the system (see Fig. 1). CESI-SIRF provides stroke location coordinates in World Geodetic Coordinate System 1984 (WGS84). The accuracy is estimated to be about 500 m for both x and y coordinates. The CESI-SIRF system groups within a single flash each signal detected within one second and within a 10-km radius around the first detected stroke; the estimated current intensity corresponds to the largest among the group of detected strokes. The electromagnetic field sensors of the Italian LLS allow detecting a stroke having a minimum current of about 2 kA. A single sensor measures the field in a so-called nominal range of 370 km. This ensures a detection efficiency for low currents of roughly 90% up to 200 km, which is also the mean baseline for the Italian sensors. This turns into a global detection efficiency of 90% over the Italian territory. (See [9,10] for additional details).

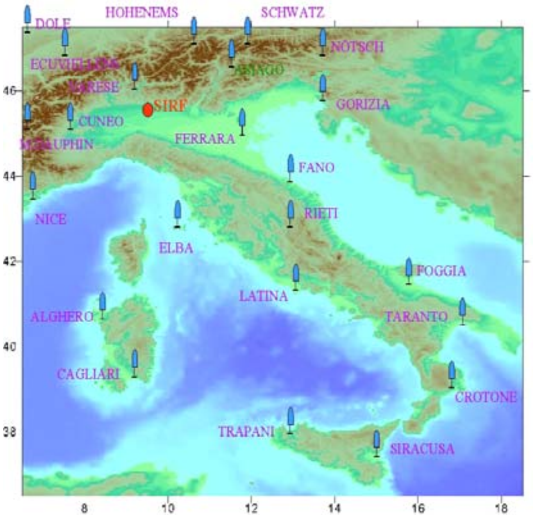

Fig. 1 – Italian lightning location system CESI-SIRF: sensor locations.

2.2. The Italian monitoring systems for protection manoeuvres CESI-SAM

The Italian monitoring systems for protection manoeuvres SAM (‘Sistema Acquisizione Manovre) consists of a number of PC-based recording systems installed at some primary substations of the Italian MV power network, each receiving signals from the different protection devices of the lines connected to the given substation, namely: overcurrent, 0-sequence and breaker intervention relays. The system, having a 10-ms sampling time, is provided with an internal clock synchronized with the UTC time, which gives the required synchronization between lightning CESI-SIRF data and MV network data, and records any status change for each protection device in an ASCII file that can be post-processed (see [7] for further details).

2.3. LIOV-EMTP code for the calculation of lightning induced voltages on realistic power distribution systems

The LIOV-EMTP code is the result of the merging of the LIOV code [11-13,17-19] and the Electromagnetic Transient program, EMTP [20,21].

The LIOV code, in particular, is based on the field-to-transmission line coupling formulation of Agrawal et al. [22], suitably adapted for the case of an overhead line above a lossy ground. The equations are numerically solved using a finite difference time domain (FDTD) approach. A specific routine is implemented to calculate the electromagnetic field originated by indirect lightning, by adopting the MTLE return-stroke engineering model [11,23] and by using the Cooray-Rubinstein formula [24,25], improved according to the remarks by Wait [26], to take into account the finite value of the ground resistivity in the field calculation. Concerning the effect of the ground resistivity in the calculation of the line parameters, with particular reference to the ground impedance, the Carson expression [27] is adopted. Indeed, LIOV being a time-domain code, the ground transient resistance formula derived by Timotin [28], which corresponds to the Carson formula, is employed. Recently, the expression proposed in [29] has been introduced in the LIOV code, which corresponds to the more general Sunde’s expression for the ground impedance [30].

The LIOV code allows for the calculation of lightning-induced voltages along a multiconductor overhead line as a function of lightning current waveshape (amplitude, front steepness, and duration), return stroke velocity, line geometry (height, length, number and position of conductors), values of resistive terminations, ground resistivity and relative permittivity. It allows also taking into account induction phenomena due to the downward-leader field [31], non-linear phenomena such as corona [32] and the presence of surge arresters [18]. For convenience, we shall call the model of a LEMP-illuminated line as ‘LIOV-line’.

To take into account the presence of more complex types of terminations, as well as of line discontinuities and complex system topologies, the LIOV code has been interfaced with the well-known electromagnetic transient program, EMTP. Following a similar approach as in [33], the distribution system is considered as a set of LIOV-lines connected to each other through shunt admittances; these admittances represent the boundary conditions for each line termination and can take into account the presence of surge arresters, of shielding wire multiple groundings, of distribution transformers and of any other power component modelled in the library of such electromagnetic transient programs. The calculation of the induced voltages is performed at each time step in two phases:

– the response of each illuminated line is calculated by the LIOV code;
– the task of solving the boundary conditions (which can involve rather complex differential equations) is assigned to the EMTP.

The specific interface realized to link the LIOV code and the EMTP is described in Fig. 2 [13]. It does not require any modification to the source code of the EMTP: the modified LIOV code is indeed contained in a dynamic link library, called within the TACS environment. The data exchange between the LIOV code and the EMTP is realized in the following way: the induced currents at the terminal nodes, computed by the modified LIOV code are input to the EMTP via current-controlled generators, and the voltages calculated by the EMTP are input to the modified LIOV code via voltage sources. The link between the LIOV-line and the EMTP line terminations, is realized by means of a short lossless line.

The LIOV-EMTP code has been successfully tested against experimental results obtained through EMP simulators and real scale experiments, as shown in Figs. 3 and 4.

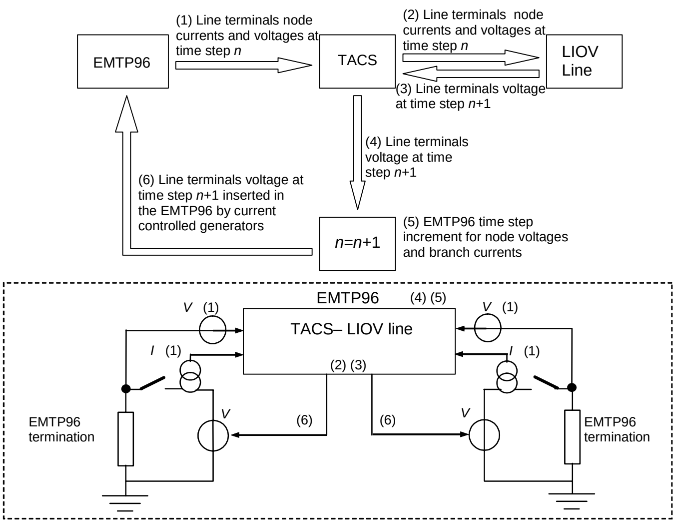

Fig. 2 – Scheme of the developed interface of the LIOV code with EMTP. Adapted from [13].

2.4. Correlation procedure

The developed procedure is aimed at correlating lightning events detected by CESI-SIRF with the relays operation detected by CESI-SAM. Three criteria have been conceived to correlate lightning to fault events. It is important to note that with 'fault event' we mean an event which produces a status change of a relay relevant to a specific line (which, also depending on the distribution transformer connection to ground will or will not be associated with a voltage dip).

Correlation criteria:

1. *Time correlation criterion*: each lightning event is considered correlated to a fault event if it occurred within ± 1 s (GPS time) from the fault event occurrence;
2. *LIOV-EMTP correlation criterion*: each lightning event is considered correlated to a fault event if the voltages calculated using LIOV-EMTP at a significantly large number of observation points all along the system, exceed the critical flashover voltage of the system.
3. *Time and LIOV-EMTP correlation criterion*: each lightning event is considered correlated to a fault event if both criteria 1 and 2 are satisfied.

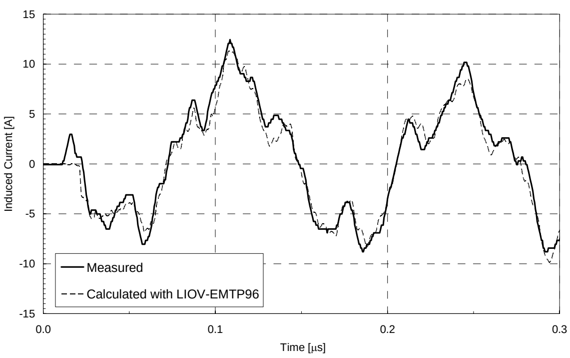

Fig. 3 – Comparison between simulated and measured induced currents at a bus of a single-wire, reduced scale, 24-line network, illuminated by the electromagnetic field generated by the EMP Simulator of the Swiss Defence Procurement Agency, VERIFY, at Spiez, Switzerland. Adapted from [14].

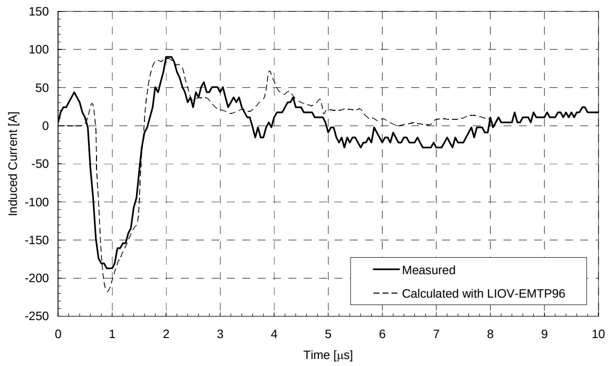

Fig. 4 – Comparison between simulated and measured lightning-induced currents on a phase conductor of the overhead experimental line at the ICLRT (International Center for Lightning Research and Testing) of the University of Florida. The line consists of 4 conductors (3-phase conductors plus neutral), 15 poles and is equipped with surge arresters, groundings of the neutral conductor and termination resistors. The stroke location is 15 m from the line. (See [34] for details)

Concerning correlation criterion #2, the calculation of the lightning-induced voltages is performed as follows: as LEMP-inducing effects are negligible for those network portions of the system that are located some kilometres away from the stroke location, the calculation of lightning-induced overvoltages is limited to those portions of the system nearer to the stroke location. In particular, for each stroke location only those lines having one termination located within a circle of 2-km radius or lying within that circle (even with both terminations out of it) have been considered as LEMP-illuminated and consequently included in the calculations (see Fig. 5). A rationale for the 2-km value is given in [35]. Concerning the terminations of the illuminated sub-portion of the system, when they are not connected to any other line, they are assumed to be connected to a distribution transformer, approximated by a capacitive equivalent circuit, while when they are connected to another line external to the circle, they are considered closed on the surge impedance matrix, as illustrated in Fig. 5.

The lightning current waveshape is assumed to be trapezoidal, with variable rise time. As LLS do not provide any information concerning the rise time of the lightning current, such a parameter has been varies in the range 1-3 μs.

Now each lightning stroke is considered potentially correlated to a fault event when the induced overvoltages, calculated by using LIOV-EMTP, plus the industrial frequency one, exceeds the critical flashover voltage (CFO) of the line[1].

The steady-state voltage at industrial frequency is taken into account as a uniformly distributed. This means that three probabilities of flashovers are therefore obtained for each phase of the overhead line, which allow to infer the type of fault event (phase-to-ground or phase-to-phase), if any. In particular, if the probability of a given fault is larger than 80%, the specific fault is assumed to occur.

It is worth noting that correlation criterion #1 selects also fault events with stroke location which are not enough close to the overhead lines of the network to induce a dangerous overvoltages (e.g. more distant than 2 km). On the other hand, correlation criterion #2, which theoretically should be capable of providing a more accurate lightning-fault event correlation, is also affected by a margin of error due to the uncertainty on the following quantities: lightning current amplitude and stroke location estimated by LLS, value of ground resistivity, location of insulator chains along the overhead lines and value of the industrial frequency voltage. The third criterion, namely the satisfaction of criteria 1 and 2, should in principle avoid some of the above-mentioned uncertainties. In other terms, we can say that

[1] The CFO is generally determined for the 'standard' 1.2/50 μs waveshape multiplied by a correction factor, which accounts for the narrower shape of the induced voltage waveform compared to direct ones [35,36]. This issue, however, certainly deserves further investigations.

criterion #2 provides a set of potential candidates of fault events which are considered correlated to lightning events only if criterion #1 is also satisfied.
Due to the above mentioned uncertainties, the CFO correction factor (see note 1) has been fixed to 1.

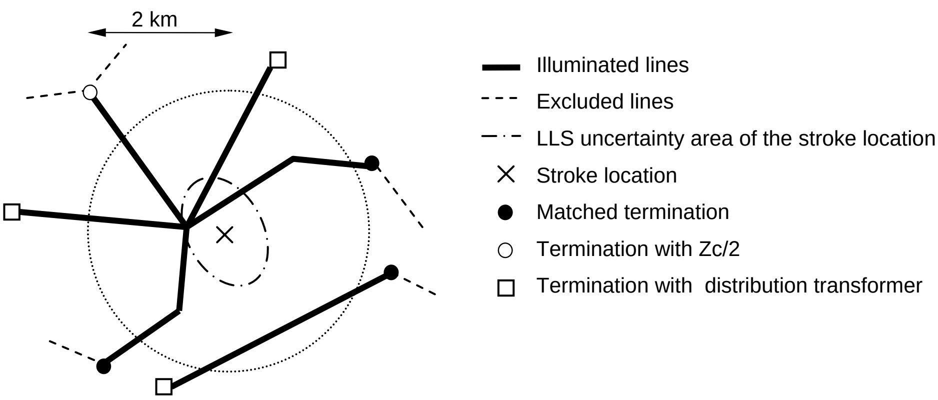

Fig. 5 – LEMP-illuminated part of the network.

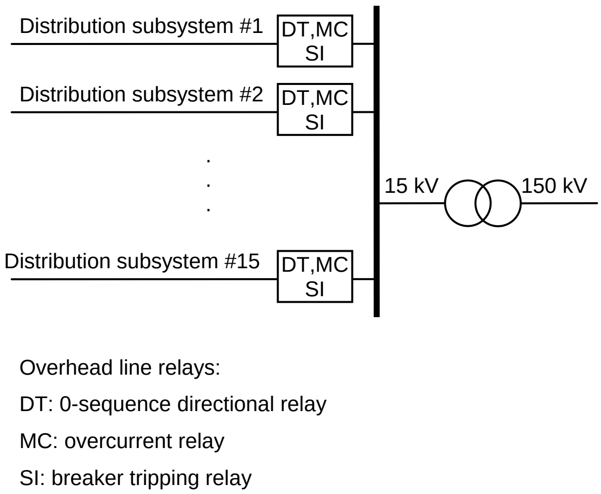

Fig. 6 – Protection system relays installed at the substation of the MV distribution system under study.

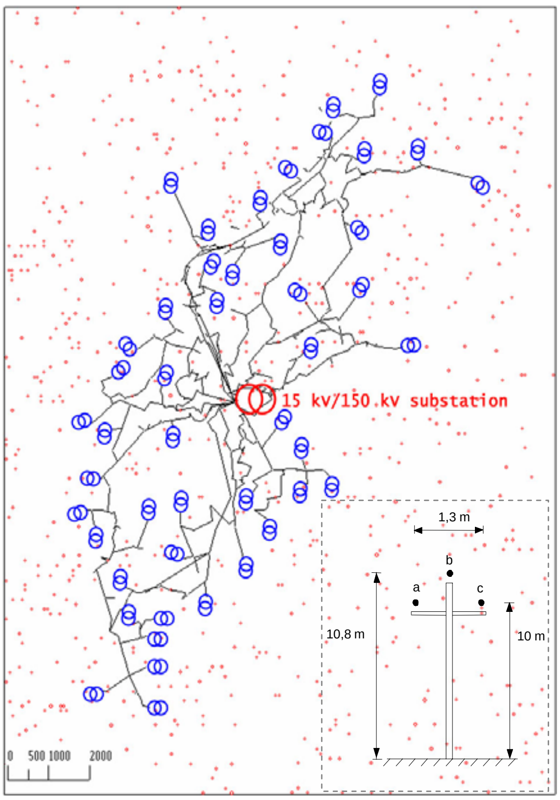

Fig. 7 – Top view of the MV distribution network with stroke locations recorded in one year (1999) by the Italian LLS CESI-SIRF. Geometry of the network poles is represented in the inlet.

2.5. Application of the proposed procedure to an Italian distribution system

The considered network is located in the northern part of Italy in a region where the average value of ground conductivity is 0.001 S/m [3,7]. It is composed by 15 different subsystems supplied by one 15 kV/150 kV substation as shown in Fig. 6 and 7. In Fig. 6, the three types of relays at the substation of the system are shown. The rated r.m.s. value of the phase-to-phase voltage is 15 kV and the CFO of the overhead line is 125 kV. The geometry of the overhead lines poles is shown in Fig. 7 which also

reports the lightning stroke locations recorded by the Italian LLS in the period 01/01/99 – 31/12/99, considered for the analysis.
Table 1 reports the summary of the fault events correlated to lightning determined by adopting the procedure described in section 2.4[2].
Adopting only criterion #1 it is found that the number of correlated lightning-faults events is 30 (14 single-phase and 16 multi-phase faults). Criterion #2 produces a set of 32 candidates (11 single-phase and 21 multi-phase). The combined use of the above correlation criteria produce a number of lightning-correlated fault events equal to 8 (4 single-phase and 4 multi-phase), which is a more reliable result than those obtained by adopting criterion #1 or #2 separately. This can be explained observing, as mentioned in Section 2.4, that the separate use of correlation criterion #1 or #2 is affected by the above mentioned approximations, which result in overestimating the number of correlated events.

Tab.1 –Lightning events correlated with relay operations for the distribution system under study in the period 01/01/99 – 31/12/99.

	Faults events correlated to lightning according to criterion #1 (*time* correlation)	Candidate faults events determined by using criterion #2 (*LIOV-EMTP* correlation) (*)	Faults events correlated to lightning according to criterion #3 (*time* and *LIOV-EMTP* correlation)
Number of single-phase faults events	14	11 (6)	4
Number of multi-phase faults events	16	21 (13)	4

(*) in parenthesis the number of events estimated locating the observation points along the various lines only at the line terminations.

3. STATISTICAL EVALUATION OF THE LIGHTNING PERFORMANCE OF DISTRIBUTION LINE: INFLUENCE OF SOIL RESISTIVITY AND PRESENCE OF SURGE ARRESTERS

In this paragraph we calculate the indirect lightning performance of an overhead distribution line, having the poles with the same geometry of Fig. 7, by using a statistical procedure based on the Monte Carlo method. The method is thoroughly presented in [15,16,37]. The Monte Carlo method is applied to generate a significant number of events (al least 10^4). Each event is characterized by five random variables: the peak value of the lightning current I_p, its front time t_f, the two co-ordinates of the stroke location and the value of the industrial frequency voltage for each phase. Such events are generated assuming the statistical distributions of lightning current parameters reported in [39], disregarding the possible bias in the amplitude distributions introduced by the attractive radius of the instrumented tower [37]. The stroke locations are uniformly distributed within a ‘striking area’ around the line, wide enough to include all the lightning events that can induce a voltage with maximum amplitude larger than the considered insulation level.
Concerning the evaluation of the lightning-induced voltages, the procedure exploits the LIOV-EMTP capabilities discussed above. This allows to evaluate the lightning performance of distribution lines taking into account more realistic configurations than those usually considered in the literature, namely lines above a lossy ground provided with shielding wires or neutral conductors with periodical groundings, presence of surge arresters and also of the line steady-state (industrial frequency) voltage.
In order to distinguish between direct and indirect strokes, the indirect lightning performance of the line is calculated by using the lateral distance expressions adopted in [38].
For our analysis, we have considered a 1.8-km long line above a perfectly and lossy ground, matched at both ends, with different positions of the surge arrester stations, namely at 1800 m, 900 m, 600 m, 300 m and 150 m for each other. The type of arresters considered for the simulation has a rated voltage of 15 kV and a typical non-linear V-I characteristic used in the Italian distribution system.

[2] No significant differences in the results have been obtained by varying the rise time of the lightning current in the assumed range 1-3 μs.

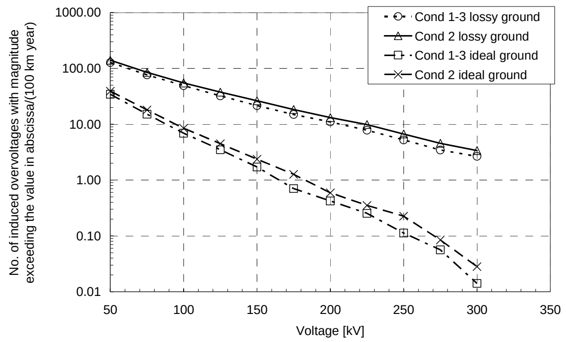

Fig. 8 – Indirect - lightning performance of an Italian MV line for the case of an ideal (perfectly-conducting) ground and for the case of a lossy ground with conductivity equal to 0.001 S/m, and for a ground flash density equal to 1flash/km2/year.

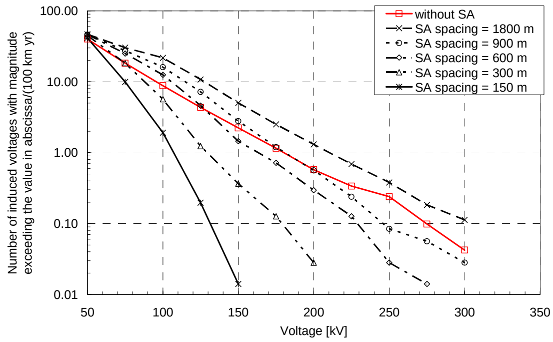

Fig. 9 – Indirect - lightning performance of an Italian MV line without surge arresters (in red) and with the presence of surge arresters, located with the various spacing values of the legend, assuming the ground ideal and a ground flash density equal to 1flash/km^2/year.

Fig. 8 shows the results obtained with two different ground conductivities, namely σ_g=0.001 S/m and ideal ground. It can be observed that lower values of ground conductivity result in larger number of overvoltages exceeding flashover rates, a result which is explained by the fact that, the ground resistivity enhances – in general – the induced voltages [35,40].

Fig. 9 shows the results of the statistical analysis illustrating the effect of the presence of surge arresters. The results refer to the annual number of induced voltages that exceed the value in abscissa / 100 km / year. The obtained results show that, for the considered line, the number of faults due to lightning-induced voltages can be significantly reduced using a spacing between surge arrester stations around 150÷300 m. It is also interesting to observe that for line configurations having a limited number of arrester stations (e.g. 1 surge arrester station each 1800 m) the presence of such components results in a decrease of the line performances, in agreement with the results reported in [18].

4. CONCLUSIONS

In order to be properly used to assess the impact of lightning-induced overvoltages on the power quality of distribution networks, Lightning Location Systems (e.g. the Italian CESI-SIRF) must be suitably integrated in a larger framework, including also monitoring system (e.g. the Italian CESI-SAM) and accurate models/computer codes for the calculation of overvoltages due to indirect lightning (as the LIOV-EMTP code). Such an integrated system represents a powerful tool for power quality monitoring in distribution networks. It can allow estimating the number of voltage dips occurring during thunderstorms that can be ascribed to lightning or to other natural causes and can find useful application in insulation/protection coordination as well as maintenance-scheduling of distribution systems.

Future improvements and developments are needed with particular reference to LLS uncertainties on lightning current amplitudes and stroke locations estimation. Also, the modelling of lightning-induced voltages needs the taking into account of additional features, which have been deliberately disregarded in the present paper, such as corona effect, tortuosity of the lightning channel and upward leaders.

The paper has also illustrated the application of a statistical procedure, based on the Monte Carlo method and the LIOV-EMTP code, which allows an improved evaluation of the lightning performance of distribution lines with reference to indirect lightning. The results obtained by using such a procedure, which allows to take into account the soil resistivity in the LEMP calculation, the industrial frequency voltage, as well as the presence of surge arresters, show that the ground resistivity produce a worsening of the lightning performance of the distribution line concerning indirect lightning. Significant improvements can be obtained using surge arresters with a spacing of 150÷300 m from each other.

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